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3-D Vector Flow Using a Row-Column Addressed CMUT Array

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ABSTRACT

This paper presents an in-house developed 2-D capacitive micromachined ultrasonic transducer (CMUT) applied for 3-D blood flow estimation. The probe breaks with conventional transducers in two ways; first, the ultrasonic pressure field is generated from thousands of small vibrating micromachined cells, and second, elements are accessed by row and/or column indices. The 62+62 2-D row-column addressed prototype CMUT probe was used for vector flow estimation by transmitting focused ultrasound into a flow-rig with a fully developed parabolic flow. The beam-to-flow angle was 90°. The received data was beamformed and processed offline. A transverse oscillation (TO) velocity estimator was used to estimate the 3-D vector flow along a line originating from the center of the transducer. The estimated velocities in the lateral and axial direction were close to zero as expected. In the transverse direction a characteristic parabolic velocity profile was estimated with a peak velocity of 0.48 m/s \pm 0.02 m/s in reference to the expected 0.54 m/s. The results presented are the first 3-D vector flow estimates obtained with a row-column CMUT probe, which demonstrates that the CMUT technology is feasible for 3-D flow estimation.

Keywords: 3-D Vector Flow, Row-Column Array, CMUT, Medical Ultrasound

1. INTRODUCTION

Blood flow velocity estimation is a widely used diagnostic tool in the clinic.¹ With spectral Doppler or color Doppler techniques, it is possible to estimate blood flow movement towards or away from the transducer. This technique is valuable when peak velocities in a vessel are needed or when an orientation of where blood flow is present. The drawbacks of these techniques are that they are limited to 1-D flow. Newer approaches as speckle tracking,² directional beamforming³ and transverse oscillation (TO)⁴ solved this limitation and were able to estimate 2-D in-plane velocities, thereby providing a more realistic representation of the blood flow movement. However, 2-D vector flow does not reveal the true dynamics of the blood flow, since it propagates in all three directions.⁵ Getting a better understanding of the dynamics of a complex flow pattern, would probably help diagnosing critical diseases at an earlier stage, thereby improving treatment success rates. Therefore, 3-D ultrasound velocity estimation attracts increasingly more attention, as it provides additional diagnostic tools for clinical purposes in real-time.

To estimate real-time vector flow in 3-D, a 2-D transducer array is required. A 32x32 element fully addressed 2-D matrix array (Vernon S.A., Tours, France) was recently used to estimate 3-D Doppler in the heart⁶ and has also been used for 3-D vector flow imaging.^{7,8}

However, fully addressed matrix arrays face issues. Consider a fully addressed matrix array with $N \times N$ elements. The total number of interconnections in these arrays scale with N^2 , which even for only a 32x32 array causes

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extensive fabrication challenges. Moreover, since a pitch of $\lambda/2$, where λ is the wavelength of the transmitted wave, is preferable to suppress grating lobes, the physical footprint of such a transducer is relatively small when the total number of interconnections is kept at a reasonable level.

To overcome the challenges with 2-D matrix probes, the idea of row-column (RC) addressed arrays emerged.^{9,10} They work as two $N \times 1$ and $1 \times N$ wide linear transducers mounted orthogonally to each other to jointly form a 2-D array (see Fig. 1). In transmit, only row-elements or column-elements can be excited, whereas channel data in receive can be acquired for both rows and columns simultaneously. The benefits of RC arrays are that a large footprint can be obtained while maintaining a pitch of $\lambda/2$ and further having the number of elements reduced. In this study, we show that 3-D realtime vector flow using TO can be obtained using an in-house-developed RC addressed $62 + 62$ element prototype CMUT (capacitive micromachined ultrasonic transducer) probe,^{11,12} assembled by Sound Technology, Inc. (State College, PA, USA).

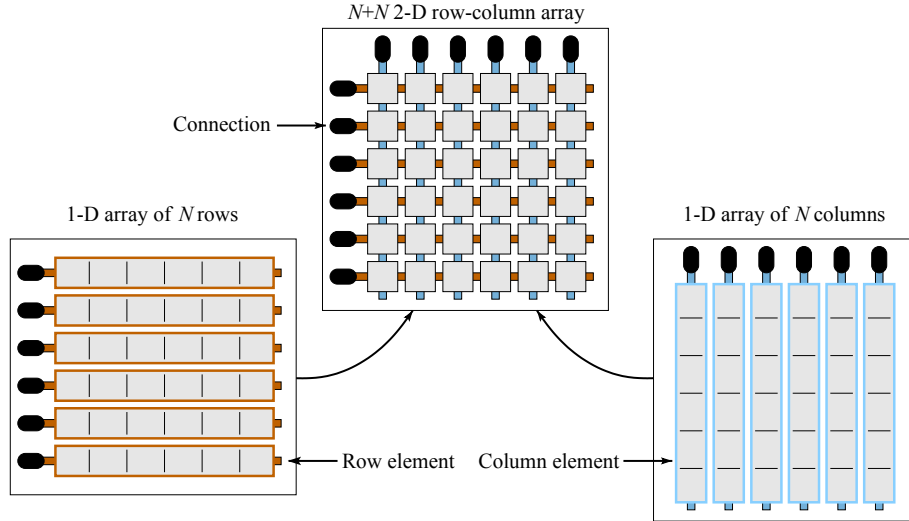


Figure 1: In a RC addressed array, two $1 \times N$ and $N \times 1$ arrays are mounted orthogonally on each other, thereby jointly forming a 2-D array of $N + N$ elements. The row elements and the column elements can be viewed as two wide 1-D linear arrays without elevation focus. In a RC array, the number of interconnections is reduced to $2N$. Modified from¹³

2. CMUT TECHNOLOGY

Currently, the vast majority of commercial ultrasound transducers are made by dicing the individual elements from a piezoelectric material. When a voltage is applied across them, a deformation will occur and a pressure field is generated. Conversely, a deformation of the piezoelectric material from an external pressure will generate a voltage difference across the crystal. Another technique with similar properties are the CMUTs. Unlike piezoelectric ultrasound transducers that are fabricated with mechanical processes, CMUTs are lead free and fabricated using microelectromechanical systems (MEMS) technology, where structures in the order of microns can be manufactured. This technology offers the possibility of developing nerly kerf-less transducers with almost any choice of pitch, customized geometries, broadbanded transducers with high sensitivity, and at much lower fabrication cost.

The pressure field generated with a CMUT originates from small vibrating CMUT cells. A cross section of such a single CMUT cell is seen on Fig. 2. The task is to generate a CMUT cell, which can vibrate such that ultrasonic waves can be transmitted and received. The CMUT technology works as following; At rest, no voltage is applied to the electrodes and the top plate is unbent. Applying a DC-voltage across the top and bottom electrode, "pulls in" the top electrode and works as the new starting point for the cell. The closer the top electrode can be pulled in, the higher is the obtained sensitivity (unless a complete pull in is made, which collapses the cell). An ultrasound pressure field is generated by applying a sinusoidal AC-voltage across the cell,

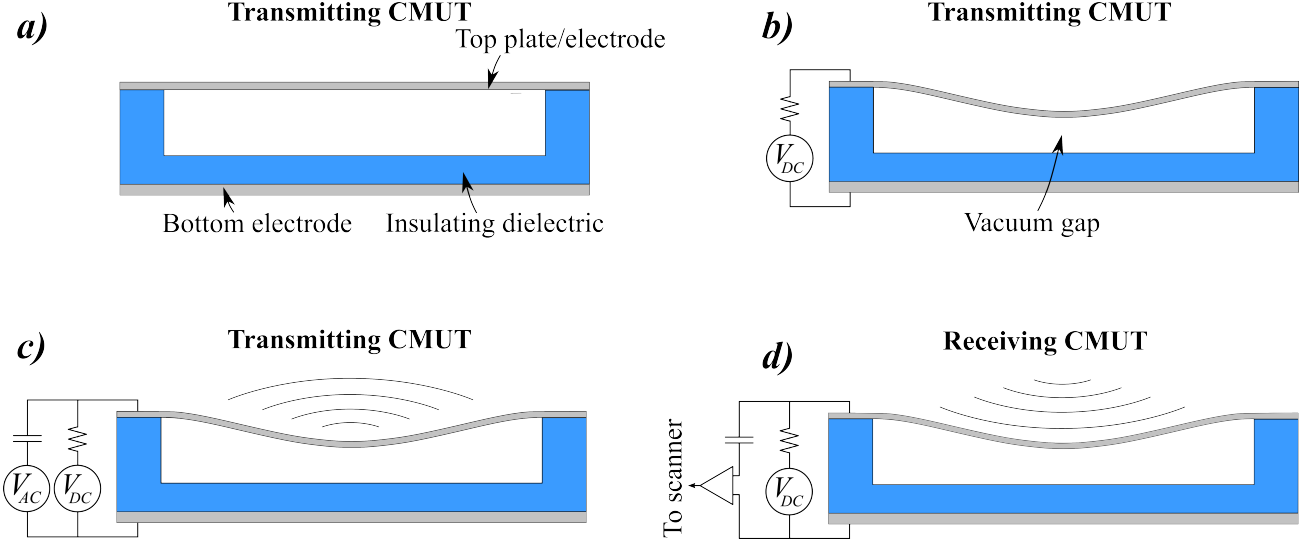


Figure 2: The illustration shows the cross section of a single circular CMUT cell. In a) the initial cell is shown. A DC voltage is applied in b) to pull the top electrode closer to the bottom electrode. The same DC voltage remains throughout both transmit and receive. When the AC voltage is applied the top electrode starts to vibrate around the starting point in c) and ultrasound is transmitted. In receive d), the returned pressure echo will result in a vibrating top electrode which induces a current which is sampled in the ultrasound scanner.

which induces a vibration on the top electrode. In receive the AC-voltage is disabled and the returning echo causes the top electrode to vibrate which generates a signal which is sampled using the connected ultrasound scanner. Each element in a CMUT consists of several CMUT cells that can vibrate in phase to increase the transmitted pressure field. 1-D prototype CMUTs have been manufactured with success,¹⁴ whereas 2-D CMUTs have until now, only been reported for experimental use.^{11,12,15} The presented prototype 2-D RC CMUT probe relies on the described CMUT technology.

3. METHOD

The following section briefly describes how an M-mode sequence for 3-D vector flow estimation was designed, and how data was sampled and processed.

3.1 Transmit sequence

An interleaved M-mode sequence where focused emissions alternately were emitted from either row elements or column elements was designed, see Fig. 3. The focal depth was 3 cm, which was also the distance to the center of the vessel. A total of 20 frames, each consisting of 2×32 emissions were recorded and stored for offline processing.

3.2 The transverse oscillation estimator

A 3-D version of the transverse oscillation (TO) method was used as the velocity estimator in this study.^{4,16} The basic principles of TO is to generate a double oscillating field in receive by applying two symmetric apodization peaks spaced by a distance d . Two lines are then beamformed separated by a distance of $\lambda_x/4$ within the double oscillating field, where the depth dependent transverse wavelength is given by

$$\lambda_x(z) = 2\lambda_z \frac{z}{d}, \quad (1)$$

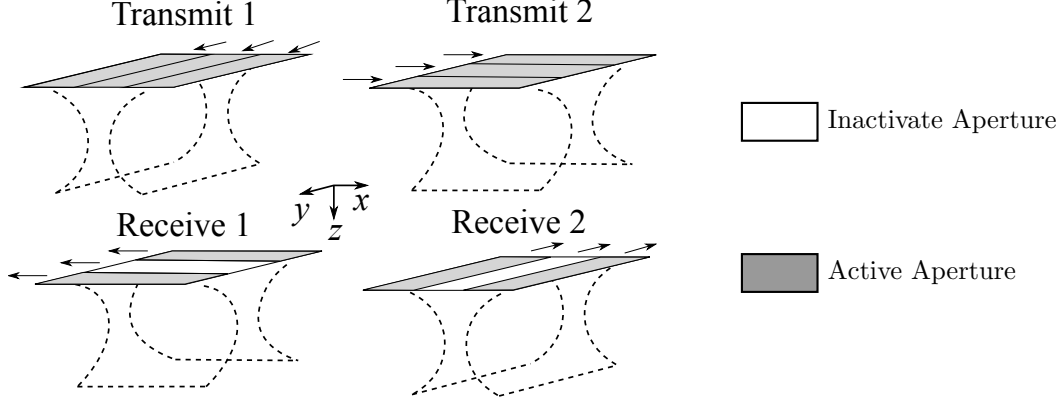


Figure 3: Illustration of the interleaved transmit and receive setup. In the first transmit event, electronically focused ultrasound is emitted with all row elements (transmit 1) and received on the column elements (receive 1). In the second transmit event, the orthogonal scenario is applied, such that focused ultrasound is emitted with all column elements (transmit 2) and received with row elements (receive 2). The inactive aperture is illustrated as white elements, whereas gray elements depicts the active aperture according to the required TO apodization profiles.

with z being the depth and λ_z the wavelength of the emitted signal. The two beamformed lines can be combined to estimate the velocity component v_x , transverse to the receiving elements. The same procedure is used for estimating the lateral velocity component v_y , but this time, the transmit/receive elements are flipped i.e., for v_x transmit is made on row elements and receive on column elements, and for v_y , transmit is made with column elements and received with row elements. Due to the symmetry of the RC probe, it is anticipated that the lateral wavelengths λ_y and λ_x are equal. The last velocity component v_z is calculated using a traditional autocorrelation approach¹⁷ from either of the transmit events. Note here that the three velocity components are obtained simultaneously due to the inter spacing of the emissions. The three estimated velocities v_x , v_y and v_z are subsequently combined to yield 3-D vector flow along one line.

3.3 Data processing

Although RF data was accessible from both row and column elements, only data from the non-transmitting elements was processed i.e. when transmitting with rows, data from columns was processed and vice versa. An in-house developed beamformer was used to beamform the data.¹² A traditional TO apodization profile was used in the beamforming, where two peaks each spanning 25 elements were separated by 37 elements. The TO estimator was used for 3-D vector flow estimation as has been shown in previous work.¹⁶ Specifications for the TO apodization in receive are seen in Table 1. Stationary echo canceling was performed by subtracting the mean values from each pair of 32 emissions from each beamformed line.

4. MATERIALS & EQUIPMENT

4.1 The 62+62 prototype CMUT probe

A prototype 2-D RC CMUT was used for conducting the measurements. Each side of the RC transducer contained 64 elements, 128 elements in total, where 4 elements were used for integrated apodization purposes.^{11,12} The center frequency was 3.0 MHz, the pitch was 270 μm which approximately corresponds to a $\lambda/2$. Each element consisted of 1210 small CMUT cells that could be excited simultaneously and vibrate in phase. The length of each CMUT cell was 56 μm and the top plate thickness was 1.85 μm , see Table 1. An image of the disassembled CMUT probe is seen in Fig 4.

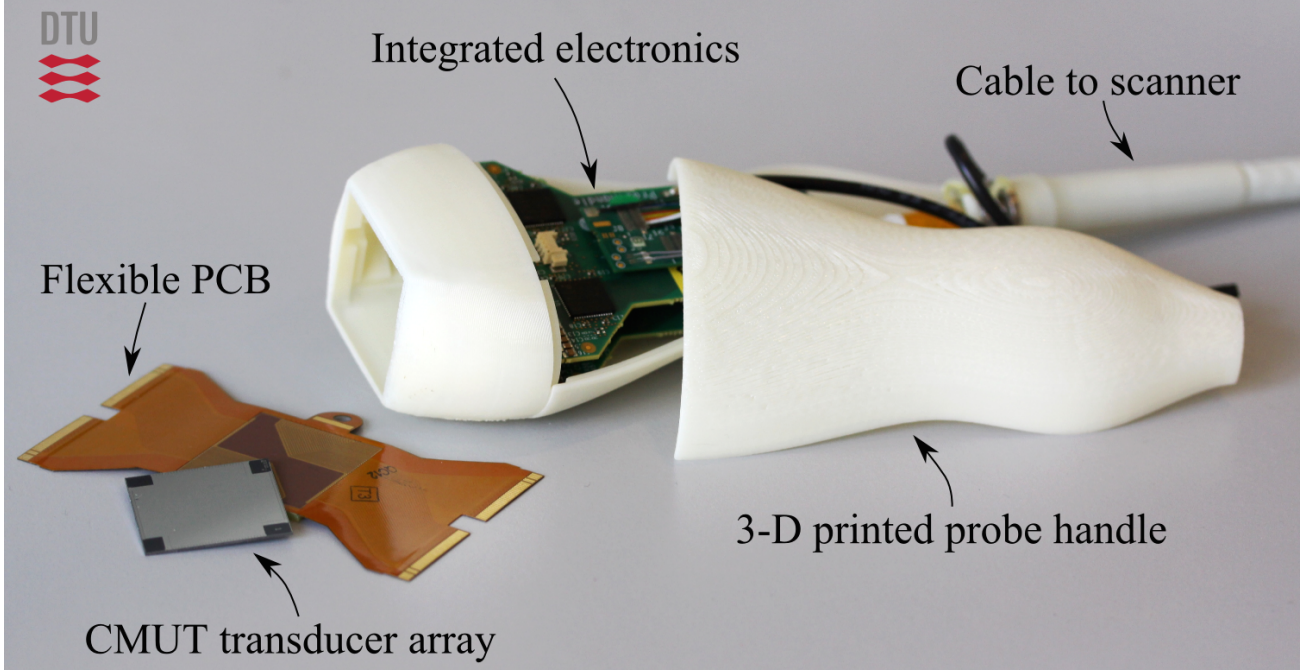


Figure 4: Image showing the disassembled probe with its main components: The CMUT array, which is mounted and wire-bonded on the flexible printed circuit board (PCB), the 3-D printed probe handle and the integrated electronics. From.¹⁸

4.2 Experimental scanner

The RC CMUT was connected to the experimental ultrasound scanner, SARUS¹⁹ from which raw RF data was acquired for all 128 channels. The applied DC bias voltage was 190 V and the transmit voltage used was 75 V. Data were acquired at a sampling frequency of 70 MHz. The data was stored and processed offline.

4.3 Flow-rig

An in-house built flow-rig system was used for validation of the estimated 3-D vector flow. A centrifugal pump circulated a blood-mimicking fluid (Danish Phantom Design, Frederikssund, Denmark) in the system and a 1.2 m long inlet ensured that a fully developed laminar flow with a parabolic profile was present at the measurement site. The transducer was fixated above a rubber tube ($\varnothing = 12$ mm) at a distance of 3 cm from the center of the vessel. Based on the volume flow measured with a MAG 1100 flow meter (Danfoss, Hasselager, Denmark), the expected peak velocity v_0 was calculated and compared to the estimated profiles. An illustration of the expected velocity given the actual scan plane is seen in Fig. 5. Transducer specifications, transmit properties and other applied variables are listed in Table 1.

5. RESULTS

In Fig. 6 all three velocity components for a line perpendicular to the transducer surface are shown. The estimated velocity profile averaged over 20 frames are illustrated with the solid black line \pm one standard deviation (dotted lines). The red lines depict the expected velocity profile at a certain depth. Only motion in the transverse direction was expected, where a parabolic profile was seen (see Fig. 6a). The peak transverse velocity was $0.48 \text{ m/s} \pm 0.02 \text{ m/s}$ corresponding to a -10.9% bias compared to the expected 0.54 m/s . Estimates in the lateral (Fig. 6b) and axial (Fig. 6c) direction showed negligible flow as expected with a small mean standard deviation of $\pm 0.02 \text{ m/s}$ and $\pm 0.01 \text{ m/s}$ respective. Along the central 90% of the vessel diameter, the relative

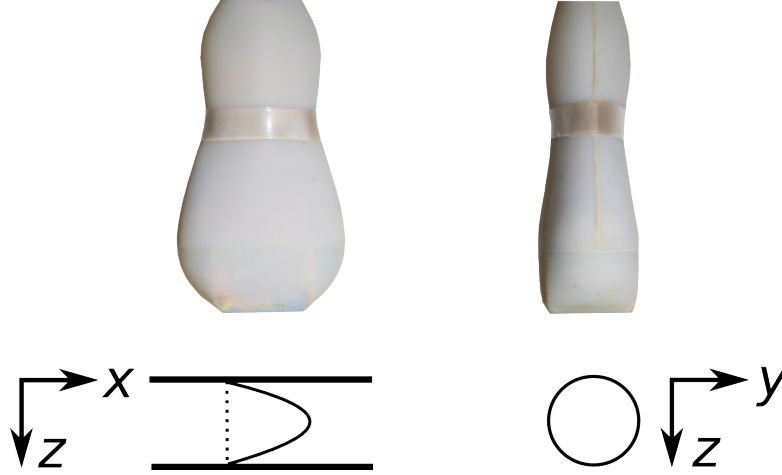


Figure 5: Illustration of the theoretical flow-rig measurement setup, where a parabolic flow profile is present in the zx -plane and no in-plane velocity is present in the zy -plane.

Table 1

Transducer & emissions sequence setup			Phantom & processing parameters		
Pitch row/column	270	μm	Focus in transmit	3	cm
Kerf row/column	2.5	μm	Vessel diameter	12	mm
Row/column elements	64	-	Peak velocity v_0	0.54	m/s
Active elements	124	-	Emissions per estimate	32	-
Sampling frequency	70	MHz	Apodization in transmit	Hanning	-
Transmit voltage	75	V	TO apodization	Hanning	-
Frames	20	-	TO peak element distance	37	-
Pulse repetition frequency	3.2	kHz	TO peak element width	25	-

mean bias was $(-4.9, -0.4, 0.5)\%$ with a mean relative standard deviation of $(6.7, 4.9, 2.5)\%$ for (v_x, v_y, v_z) respectively.

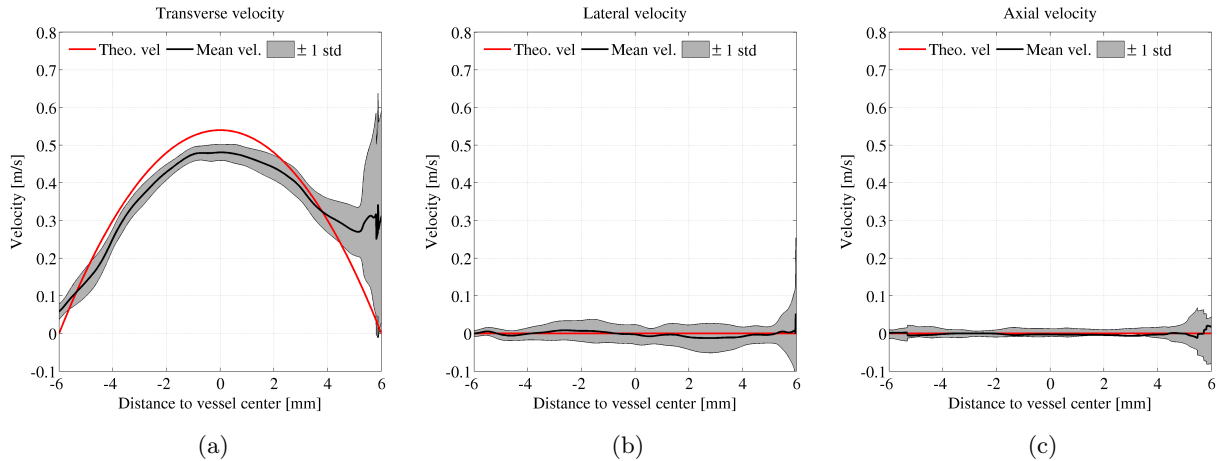


Figure 6: Measured velocity profiles (solid black line) and \pm one standard deviation (dotted lines) plotted on top of the theoretical expected velocity profile (red line) in the transverse direction (a), the lateral direction (b) and the axial direction (c). The velocity profiles are displayed across the vessel of diameter 12 mm.

6. CONCLUSION

The results show that 3-D vector flow can be obtained with a prototype 62+62 2-D RC CMUT probe in an experimental setup. A low relative standard deviation $<4\%$ was obtained for the estimated peak velocity, which translates to a high consistency in the velocity estimates. Additional measurements will explore the potential of 2-D CMUT's and clarify the compatibility with traditional piezoelectric transducers.

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